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Final Report

for

Air Force Office of Scientific Research

Grant AFOSR 77-3455

Covering the Period

September 30, 1977 - September 30, 1978

G. L. Report No. 2890

November 1978

Principal Investigator

C. F. Quate

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH (AFSC)

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ACOUSTIC MICROSCOPIC STUDY OF MATERIALS

ABSTRACT

Our research program is based upon the study of the properties of electronic microstructures with acoustic microscopy. It has a further objective of improving our understanding of this emerging technology as a new form of imaging the detail in modern microcircuits. The scope of this area is ever increasing and new methods for analyzing features on this scale are important. The theory of the acoustic microscope and the resolving power of this instrument have both been advanced during the initial period of this program. The resolving power of our best instrument is now comparable to the optical microscope. We have been able to demonstrate a new form of the microscope which is described by the term "photoacoustic microscope" and it holds the potential for revealing still more information on the detailed structure of microcircuits.

1. Report on Accomplishments

The work during the single year of this program has centered on the elastic properties of thin films as deposited on appropriate substrates. These films and their interactions with the substrate form a basic component in electronic microstructures. Our prime aim has been to use these films as a vehicle for acoustic microscopy. We want to use the elastic response as monitored in the reflection microscope as a method for revealing the physical properties of these films. The response has been used as a guide in developing the theory for acoustic micrographs. In working out the theory - a process that is still continuing - we have learned a great deal about acoustic microscopy. In particular the reflectivity of the layers can now be used in the study of subsurface details. We have worked with GaAs, Si, sapphire and quartz as substrates and with gold, aluminum and various metal oxides for the film material. We have learned that the changes in reflectivity as a function of the displacement of the reflecting surface from the focal plane of the instrument can reveal a great deal of information about the structure and composition beneath the surface. This is a region that is difficult to examine with either the optical or the electron microscope without employing destructive etching techniques. We have also learned from these studies that it is possible to observe the elastic anisotropy of the reflecting substrate.

The sensitivity of our measurement can be judged from the fact that it is now possible to distinguish the [100] face in silicon from the [111] face. This is possible by virtue of the fact that elastic properties of silicon are anisotropic. Gallium Arsenide is also elastically anisotropic and when this is

included in theory we can account for all of the details in the measured curves. The theory of acoustic imaging in reflection has been worked out in detail. It is reported in a paper by A. Atalar entitled "An Angular Spectrum Approach to Contrast in Reflection Microscopy" as published in the October 1978 issue of the Journal of Applied Physics.

In another major part of the program we have been successful with a high frequency instrument that has a resolving power comparable to the optical microscope. This instrument operates at 3 GHz and the wavelength of sound in water at this frequency is equal to 0.5 micrometers - a value equal to that of green light in the optical spectrum. This advance was made possible with improved techniques in lens fabrication and transducer technology. This has permitted us to reduce the diameter of the acoustic lens in the sapphire crystal to a value less than 40 micrometers. We have been able with this high frequency unit to image the gate region of a dual gate FET fabricated at the Hewlett-Packard Laboratories which consists of lines one micrometer in extent and spaced by one micrometer. We have also been able to image structure beneath the aluminum metallization in silicon transistors and demonstrate significant differences between the optical and the acoustic images. This work has been written up and published (see Section 2, Ref. No. 1).

Following the outline of the work initially proposed for this research program we can report that we now have a microprocessor (Cromemco Z-2) tied into our microscope. We have finished the program which allows us to store an acoustic image on a floppy disc in digital form. The image array is 256 points by 256 lines and it is 8 bits deep. The 8-bit storage system is adequate

for the image but it is inadequate for sampling the scan lines. The scan in this microscope is sinusoidal rather than linear. To accurately sample and store the position of the object it will be necessary to use a 12 bit A to D converter. This is on order and when installed it will remove the small residual distortion in the stored image. The image as stored in digital form will be processed with several techniques in order to determine the proper techniques for enhancing the image.

The work on the fast scanning system is near completion. We have rebuilt the system so that the sample is moved in the y-direction at a rate of 1 KHz and the lens is moved in the x-direction at the rate of 10-15 Hz. The first images with the system look respectable - but it has not yet been incorporated into an operating system.

The system which uses an acoustic cell with parallel faces and variable length for measuring liquid absorption has been finished and is now undergoing final calibration. We have a heater and thermometers mounted directly on the crystal faces so that we can control and measure the liquid temperatures with great accuracy. Our purpose will be an exploration of the acoustic properties of various liquids at microwave frequencies and carry out an extended search for low loss liquid. If we are successful in this it would permit us to use acoustic waves with shorter wavelengths and thereby improve the resolving power of the acoustic instrument.

We have worked on the problem of measuring stress profiles but we do not yet have a definitive measure of this parameter. We do find in our studies of the gate region of an MOS transistor that the patterns in the acoustic micrographs are different - very different - from those in the optical micrographs.

These differences might arise from the stress patterns in layered material but we have yet to find a way for proving this.

We are also comparing two similar devices - MOS transistors - on the same substrate which are identical in the optical micrographs but differ in their electrical characteristics. The acoustic patterns of the gate region have small differences that may one day allow us to distinguish defective devices. At present the differences are subtle and they change with the focal position of the sample. We need more work on this problem before we can understand the pattern variations in a definitive way. A publishable result in this area would be a major achievement for acoustic microscopy.

In a similar vein we continue with our interest to exploit the piezoelectric coefficient of GaAs to explore the region beneath the gate of a high-frequency GaAs-FET. There are obstacles that must be overcome and we are unable to report on this problem.

The photoacoustic experiment is another matter, however, for we do have preliminary results that indicate that this will become a viable form of microscopy. During the month of July we were fortunate in gaining access to Professor Siegman's laboratory. Siegman and J. R. Salcedo have an operating Nd-YAG laser that is mode locked and Q-switched. The mode locked pulses are 100 picoseconds in duration and, therefore, have a frequency spectrum that extends well beyond 2 GHz. We were able to focus this beam with 1 kw of peak power onto the sample and monitor the acoustic pulse that was generated with our acoustic microscope acting as a passive receiver. The focus of the acoustic lens was confocal with the focus of the objective lens used to control the optical beam. These preliminary results have been written up and submitted for publication.

This factual report - item by item - conforming to the outline of the Statement of Work - does not convey the aura of excitement that now prevails throughout the entire project. The financial support from the Air Force came at a critical time. It was sufficient to support the work on the high frequency unit at 3 GHz. That instrument is now the workhorse and we use it each week to work out problems in electronic microstructures. Many of them are furnished to us from the outside. The GaAs-FET's from Liechti at Hewlett-Packard Laboratories is one example - important, for the Air Force is also supporting some of their work.

The attitude of our visitors has also changed during this period and this is equal in importance to some of the technical problems that we are asked to explore. Gene Meieran who is in charge of Quality Control at Intel Corporation tells us that "... this is the most interesting and most exciting advance in imaging of microcircuits in the last 15 years". Graydon Larrabee, Manager of Research and Development at Texas Instruments visited with Philip Kane who is their Director of the Materials Characterization Laboratory. Larrabee observed that the instrument would give them a "new capability". He was referring to the fact that in the acoustic micrographs they could gain information on the composition of the layering structures beneath the surface. He tells us that he is going to seek approval to acquire "an acoustic instrument with a capability similar to the one (at Stanford)". Robert Burmeister who leads the Materials Group at Hewlett-Packard Laboratories has indicated that he intends to have an acoustic instrument in his laboratory in order to determine its

potential for solving some of their problems. In another area, Ted Ciszek at the Solar Energy Research Institute (SERI) in Golden, Colorado, has asked us to look at the polycrystalline silicon material that they plan to use in solar cells.

We have received support from the editorial writers in the scientific press. A write-up in the Scientific American (July 1978) in the section Science and the Citizen has brought numerous inquiries. Science magazine in the issue of 22 September 1978, described our microscope in a report by Thomas H. Maugh II. This was followed by an article in Science News (23 September 1978) by John H. Douglas. Recently the magazine Industrial Research and Development has indicated that they will publish a report on our work.

The ability to record microscopic detail with a resolution comparable to the optical microscope - coupled with our ability to sense the structuring beneath the top surface, has placed us in a strong position. An important segment of the microelectronics profession is intensely interested in our work. We are being inundated with samples. The requests exceed our capacity and we are now very selective in accepting requests.

A milestone has been passed in this critical year. We are getting serious attention from the profession and we want to respond to this - but in a limited way. We want to reserve the major portion of our program for research on acoustic microscopy. There is so much to understand. We have just acquired the ability to store images in digital form and this opens the large area of signal processing. We are just beginning in our understanding of the information

content in acoustic micrographs. We are receiving a great deal of help from those who want to assist us in this search and, in turn, this interaction permits us to keep up with the progress in their laboratories.

2. List of Publications

1. V. Jipson and C. F. Quate, "Acoustic Microscopy at Optical Wavelengths", Applied Physics Letters, 32, 789 (15 June 1978).
2. A. Atalar, "An Angular Spectrum Approach to Contrast in Reflection Acoustic Microscopy", J. Applied Physics, 49, 5130 (October 1978).
3. H. K. Wickramasinghe, R. C. Bray, V. Jipson, C. F. Quate and J. R. Salcedo, "Photoacoustics on a Microscopic Scale", Applied Physics Letters, 33, 923 (1 December 1978).

3. Presentations and Visits

By C. F. Quate

Colloquium presented to Physics Department, Dartmouth College, Hanover, New Hampshire (October 28, 1977).

Seminar at Hewlett-Packard Laboratories, Cupertino, California (November 15, 1977).

Seminar in Electrical Engineering at Bell Laboratories, Murray Hill, New Jersey (March 28, 1978).

Seminar at United Technologies Research Center, East Hartford, Connecticut (March 29, 1978).

Seminar at U.S. Steel Corporation, Monroeville, Pennsylvania

(March 30, 1978).

Invited talk at ASEE Annual Meeting, University of British Columbia,

Vancouver, Canada (June 20, 1978).

Invited talk at Rank Prize Funds "International Symposium on Electronic

Imaging", London, England (September 13, 1978).

By R. Kompfner

Invited talk at Ultrasonics Symposium, Phoenix, Arizona (October 27, 1977).

By J. Heiserman

Invited talk to the Corporate Associates, American Physical Society,

San Jose, California (October 27, 1977).

4. Visitors

October 1977

Professor Niels I. Meyer, Physics Laboratory III, The Technical
University of Denmark, Lyngby, Denmark.

Dr. C. C. Cutler, Director, Electronic and Computer Systems
Research Laboratory, Bell Laboratories, Holmdel, New Jersey.

Professor Marilyn Stockton, Dartmouth College, Hanover, New Hampshire.

Dr. Winthrop A. Baylies, Vice-President, ADE Corporation,
Watertown, Massachusetts.

November 1977

Dr. Larry Coldren, Bell Laboratories, Holmdel, New Jersey.

Professor Eric A. Ash, Department of Electronic and Electrical
Engineering, University College London, England.

December 1977

Mr. Vernon C. Westcott, Chairman of the Board, Foxboro/Trans-Sonics, Inc.
Burlington, Mass.

Dr. Michael Duffy, RCA Research Laboratories, Princeton, New Jersey.

January 1978

Dr. James C. McGroddy, Thomas J. Watson Research Center, IBM,
Yorktown Heights, New York.

Drs. R. McDonald, E. Meieran and C. Barrett, Intel Corporation,
Sunnyvale, California.

February 1978

Dr. Michael Wauk, Applied Materials Inc., Mountain View, California.

Dr. John Peschon, President, International Systems Consultants,
Palo Alto, California.

Ms. Irene Rhodes Van Dyk, Hewlett-Packard Laboratories, Santa Clara,
California.

Dr. Jacques Ruch, Bell Laboratories, Murray Hill, New Jersey.

Dr. Kumar Patel, Bell Laboratories, Murray Hill, New Jersey.

Dr. Thomas Reeder, United Technologies Research Center, East Hartford,
Connecticut.

March 1978

Dr. John T. Mendel, Electron Dynamics Division, Hughes Aircraft Company, Torrance, California.

Dr. John Moll, Hewlett-Packard Laboratories, Deer Creek, Palo Alto, California.

Dr. Burton J. McMurtry, Institutional Venture Associates, Menlo Park, California.

Dr. George R. Brewer, Manager, Electron Device Physics Department, Hughes Research Laboratories, Malibu, California.

April 1978

Dr. P. W. Anderson, Bell Laboratories, Murray Hill, New Jersey.

Dr. Ronald Moon, Varian Associates, Palo Alto, California.

Dr. Donald Hammond, Hewlett-Packard Laboratories, Palo Alto, California.

Dr. Jake Haskell, Hewlett-Packard Laboratories, Cupertino, California.

Dr. Otto Buck, Rockwell International, Science Center, Thousand Oaks, California.

Dr. Courtney Saunders, National Semiconductor, Sunnyvale, California.

Dr. G. I. Robertson, Western Electric, Engineering Research Center, Princeton, New Jersey.

Dr. Richard Lee, U.S. Steel Corporation, Monroeville, Pennsylvania.

Dr. Hank Smith, Lincoln Laboratories, M.I.T. Lincoln, Mass.

Dr. R. Bruce Thompson, Rockwell International, Science Center, Thousand Oaks, California.

Mr. Dale Ballinger, Test Instruments Division, Honeywell, Inc., Denver, Colorado.

May 1978

Dr. Shoji Wakayama, Sony Research Laboratory, Tokyo, Japan.

Dr. Robert Burmeister, Hewlett-Packard Laboratory, Palo Alto,
California.

June 1978

Dr. Simon Bennett, Department of Electronic and Electrical
Engineering, University College London, England.

Mr. Jack Baring, Honeywell, Inc. Denver, Colorado.

Dr. G. W. Bailey, Exxon Research and Development Laboratories,
Baton Rouge, La.

September 1978

Dr. Seymour Keller, Thomas J. Watson Research Center, IBM,
Yorktown Heights, New York.

Dr. William J. Spencer, Sandia Laboratories, Livermore, California.

5. Committees

Member, Defense Science Board.